Transport calculations of $\bar{p}$-nucleus interactions

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The Giessen Boltzmann-Uehling-Uhlenbeck transport model is extended and applied to the $\bar{p}$-nucleus interactions in a wide beam momentum range. The model calculations are compared with the experimental data on $\bar{p}$-absorption cross sections on nuclei with an emphasis on extraction of the real part of an antiproton optical potential. The possibility of the cold compression of a nucleus by an antiproton in-flight is also considered.

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1. Introduction

Antiproton interactions with nuclei are of big interest since they deliver the information on in-medium $\bar{p}N$ interactions [1] related to the antiproton optical potential. The real and imaginary parts of $\bar{p}$ optical potential close to the nuclear centre are still poorly known [2, 3]. As shown in [4]-[7], a deep enough real part, $\mathrm{Re}(V_{\mathrm{opt}}) = -(150 - 200)$ MeV, might cause sizeable compressional effects in $\bar{p}$-doped nuclei.

Here, we present some results of the microscopic transport simulations within the Giessen Boltzmann-Uehling-Uhlenbeck (GiBUU) model [8]. Our goal is twofold: (i) to determine the $\bar{p}$ optical potential by comparison with the data on $\bar{p}$ absorption cross sections on nuclei; (ii) to evaluate the probability of $\bar{p}$ annihilation in a compressed nuclear zone for the beam momenta 0.1-10 GeV/c.

The model is described in Sec. II. In Secs. III and IV, the calculations of $\bar{p}$ absorption cross section on nuclei and of the dynamical compression

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of the ^{16}O nucleus by moving antiproton are presented. The results are summarized in Sec. V.

2. The GiBUU model

The GiBUU model [8] solves the coupled set of kinetic equations for different hadrons (N, $\bar{N}$, Δ, $\bar{\Delta}$, π...). These equations describe the time evolution of a system governed by the two-body collisions and resonance decays. The Pauli blocking for the nucleons in the scattering final states is accounted for. Between the two-body collisions, the particles propagate according to the Hamiltonian-like equations in the mean field potentials defined by the (anti)baryon densities and currents.

We use the GiBUU model in the relativistic mean field mode. The single-particle energies $\epsilon_i = V_i^0 + \sqrt{\mathbf{p}_i^{\star 2} + m_i^{\star 2}}$ of the nucleons ($i = N$) and antinucleons ($i = \bar{N}$) depend on the effective mass $m_i^\star = m_i + S_i$, where $S_i = g_{\sigma i}\sigma$ is the scalar field, kinetic three-momentum $\mathbf{p}_i^\star = \mathbf{p} - \mathbf{V}_i$, and vector field $V_i^\mu = g_{\omega i}\omega^\mu + g_{\rho i}\tau^3\rho^{3\mu} + e_i A^\mu$. Here, σ, ω, ρ and A are, respectively, the isoscalar-scalar, isoscalar-vector and isovector-vector meson fields, and the electromagnetic field.

The meson-nucleon coupling constants $g_{\sigma N}$, $g_{\omega N}$ and $g_{\rho N}$ are taken from the NL3 set of parameters [9] of a non-linear Walecka model. The meson-antinucleon coupling constants are motivated by the G-parity transformation, however, allowing for their strengths to be rescaled by a factor $0 < \xi \leq 1$ as $g_{\sigma\bar{N}} = \xi g_{\sigma N}$, $g_{\omega\bar{N}} = -\xi g_{\omega N}$ and $g_{\rho\bar{N}} = \xi g_{\rho N}$[1].

The following two-body collision processes involving an antinucleon are implemented in the model: elastic scattering and charge exchange $\bar{N}N \to \bar{N}N$, inelastic production $\bar{N}N \to \bar{B}B +$ mesons, and annihilation $\bar{N}N \to$ mesons. Further details of the model can be found in [6, 8, 10, 11, 12] and in refs. therein.

3. Antiproton absorption and annihilation on nuclei

Fig. 1 shows the antiproton absorption cross section on ^{12}C. The GiBUU calculation without nuclear part of the antibaryon mean field ($\xi = 0$) is in a very close agreement with the Glauber model prediction [13][2].

The attractive real part of an antiproton optical potential

$$\mathrm{Re}(V_{\mathrm{opt}}) = S_{\bar{p}} + V_{\bar{p}}^0 + \frac{S_{\bar{p}}^2 - (V_{\bar{p}}^0)^2}{2m_N} \tag{1}$$

[1] Pure G-parity transformed nuclear fields are obtained with $\xi = 1$. But this leads to an unrealistically deep real part of the $\bar{p}$ optical potential, $\mathrm{Re}(V_{\mathrm{opt}}) \simeq -660$ MeV.

[2] Except for momenta less than ~ 0.2 GeV/c, where the Coulomb potential causes the deviation.

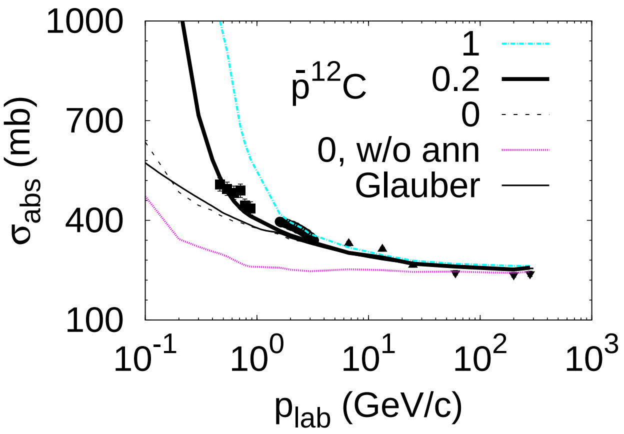

Fig. 1. (Color online) Beam momentum dependence of the antiproton absorption cross section on ^{12}C. GiBUU calculations are represented by the curves denoted by the value of the scaling factor ξ of meson-antibaryon coupling constants. The results obtained using the Glauber model [13] are shown by thin solid line. The calculation with $\xi = 0$ without annihilation is shown by dotted line. Experimental data are from [2].

bends the $\bar{p}$ trajectory towards the nuclear centre and increases the $\bar{p}$ absorption cross section. One can see from Fig. 1, that the finite values of the scaling factor $\xi \simeq 0.2$ are needed to describe the antiproton absorption cross section data at $p_{\rm lab} = 470 - 880$ MeV/c measured at KEK [2]. The best fit of the data [2] on $\bar{p}$ absorption cross sections on the ^{12}C, ^{27}Al and ^{64}Cu nuclei by GiBUU calculations is reached with $\xi \simeq 0.21 \pm 0.03$, which produces ${\rm Re}(V_{\rm opt}) \simeq -(150 \pm 30)$ MeV in the nuclear centre.

The imaginary part of the $\bar{p}$ optical potential can be calculated as

$$
{\rm Im}(V_{\rm opt}) = -\frac{1}{2} < v_{\bar{p}N} \sigma_{\rm tot}^{\rm med} > \rho_N \ , \tag{2}
$$

where $v_{\bar{p}N}$ is the relative velocity of the antiproton and a nucleon; $\sigma_{\rm tot}^{\rm med}$ is the total $\bar{p}N$ cross section including the in-medium effect of Pauli blocking for the final state nucleon in the $\bar{N}N \to \bar{N}N$ channel; ρ_N is the local nucleon density. The averaging in Eq.(2) is taken with respect to the nucleon Fermi distribution. Using (2), we obtain ${\rm Im}(V_{\rm opt}) \simeq -(105 \pm 5)$ MeV in the nuclear centre, where a small uncertainty is due to different considered nuclei. More details on the extraction of an antiproton optical potential by GiBUU calculations can be found in [12].

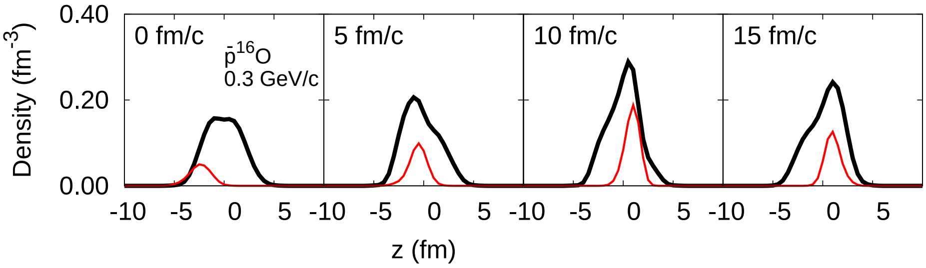

Fig. 2. (Color online) Nucleon (thick solid lines) and antiproton (thin solid lines) densities along the z-axis passing through the nuclear centre $(x, y, z) = (0, 0, 0)$ for the $\bar{p}^{16}$O system at different times. The antiproton has been initialized at the coordinates $(0, 0, -2.5)$ fm with momentum components $(0, 0, 0.3)$ GeV/c. The scaling factor of the antiproton-meson coupling constants $\xi = 0.22$ is used. Annihilation is switched-off.

4. Dynamical compression of a nucleus by an antiproton

Fig. 2 shows the time evolution of nucleon and antiproton densities for the case of an antiproton initialized at the nuclear periphery with momentum of 0.3 GeV/c directed towards the nuclear centre. The calculation has been done without the $\bar{N}N$ annihilation channel in the collision term, but allowing for the $\bar{N}N$ and NN scattering. We observe that the antiproton attracts surrounding nucleons catching them into a potential well of about $70-100$ MeV depth. The nucleon density bump moves with the $\bar{p}$ or slightly behind it due to some delay in the reaction of the nucleon density on the perturbation created by the antiproton.

The compression process of Fig. 2 has to be complemented with the calculation of an antiproton survival probability

$$P_{\rm surv}(t) = \exp\left\{ -\int\limits_0^t dt'\, \Gamma_{\rm ann}(t') \right\} . \tag{3}$$

where $\Gamma_{\rm ann} = \rho_N \langle v_{\bar{p}N} \sigma_{\rm ann} \rangle$ is the antiproton annihilation width and $\sigma_{\rm ann}$ is the $\bar{p}N$ annihilation cross section (other notations are the same as in Eq.(2)). In the case of the process shown in Fig. 2, the antiproton survives with the probability $P_{\rm surv} \sim 10^{-3}$ at the time 10 fm/c when the nucleon density maximum is reached. The experimental datection of the nuclear compression by the antiproton is only possible, if $\bar{p}$ annihilates in the compressed zone of a nucleus. The corresponding probability is $P_{\rm compr}(\rho_c) = P_{\rm surv}(t_1) - P_{\rm surv}(t_2)$, where $t_1 < t_2$ are the times delimiting the time interval, when the maximum density of a nuclear system exceeds some preselected value ρ_c. In concrete calculations, we set $\rho_c = 2\rho_0$ with $\rho_0 = 0.148$ fm^{-3} being the nuclear saturation density.

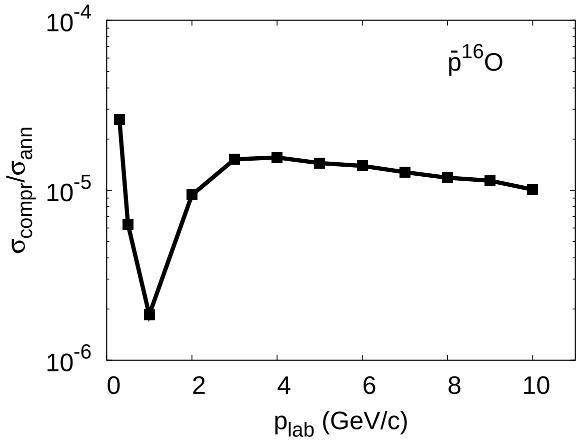

Fig. 3. The probability of antiproton annihilation at the nucleon density exceeding $2\rho_0$ as a function of the beam momentum for $\bar{p}^{16}$O collisions.

In the case of a real antiproton-nucleus collision, we apply, first, the GiBUU model in the standard parallel ensemble mode to determine the coordinates $\mathbf{r}$ and momentum $\mathbf{p}$ of the antiproton at its annihilation time moment event-by-event. Next, we initialize $\bar{p}$ at $(\mathbf{r}, \mathbf{p})$ and run GiBUU without annihilation. This allows us to compute $P_{\rm compr}$ for a given annihilation event, *i.e.* to determine the probability that this event will take place in a compressed nuclear zone. Finally, we calculate the cross section of a $\bar{p}$ annihilation in the compressed zone by weighting with the impact parameter as $\sigma_{\rm compr} = \int_0^\infty db\, 2\pi b\, \overline{P}_{\rm compr}(\rho_c, b)$, where the upper line denotes averaging over annihilation events with a given impact parameter b.

In Fig. 3, we present the probability of $\bar{p}$ annihilation in a compressed zone given by the ratio $\sigma_{\rm compr}/\sigma_{\rm ann}$, where $\sigma_{\rm ann}$ is the total annihilation cross section of $\bar{p}$ on the oxygen nucleus. The rise of the ratio with the beam momentum between about 1 and 3 GeV/c is caused by opening the pion production channels $\bar{N}N \to \bar{N}N\pi(\pi...)$, which leads to more intensive stopping of an antibaryon before annihilation, and, therefore, to larger compression probabilities.

5. Summary and conclusions

We have performed the microscopic transport GiBUU simulations of $\bar{p}$-nucleus collisions. The antiproton mean field potential has been described applying the non-linear Walecka model supplemented by appropriate scaling of the meson-antinucleon coupling constants.

The extracted antiproton optical potential from comparison with the

KEK data on $\bar{p}$ absorption cross section below 1 GeV/c is $V_{\rm opt} = -(150 \pm 30) - i(105 \pm 5)$ MeV in the nuclear centre, which is comparable with the well known phenomenological values [2, 3]. However, the BNL and Serpukhov data on $\bar{p}$ absorption above 1 GeV/c require much deeper real part of about -660 MeV, close to the G-parity value. It is important, therefore, to perform the new measurements of the $\bar{p}$ absorption cross section on nuclei above 1 GeV/c at FAIR.

The probability of the antiproton annihilation in a compressed nuclear zone is maximal at the beam momenta below 0.5 GeV/c. However, it is also big enough ($\sim 10^{-5}$) at the beam momenta from 3 to 10 GeV/c. The possibility of additional triggering, *e.g.* on a high-momentum proton, would prefer this beam momentum range with respect to the low beam momenta for the study of annihilation events in the compressed nuclear zone.

Acknowledgments

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REFERENCES

[1] E. Friedman and A. Gal, *Phys. Rep.* **452**, 89 (2007).
[2] K. Nakamura *et al.*, *Phys. Rev. Lett.* **52**, 731 (1984).
[3] E. Friedman, A. Gal, and J. Mareš, *Nucl. Phys.* **A761**, 283 (2005).
[4] T. Bürvenich, I.N. Mishustin, L.M. Satarov, J.A. Maruhn, H. Stöcker, and W. Greiner, *Phys. Lett.* **B542**, 261 (2002).
[5] I.N. Mishustin, L.M. Satarov, T.J. Bürvenich, H. Stöcker, and W. Greiner, *Phys. Rev.* **C71**, 035201 (2005).
[6] A.B. Larionov, I.N. Mishustin, L.M. Satarov, and W. Greiner, *Phys. Rev.* **C78**, 014604 (2008).
[7] I.N. Mishustin and A.B. Larionov, *Hyperfine Interact.* **194**, 263 (2009).
[8] http://gibuu.physik.uni-giessen.de/GiBUU
[9] G.A. Lalazissis, J. König, and P. Ring, *Phys. Rev.* **C55**, 540 (1997).
[10] B. Blättel, V. Koch, and U. Mosel, *Rep. Prog. Phys.* **56**, 1 (1993).
[11] T. Gaitanos, H. Lenske, U. Mosel, *Phys. Lett.* **B675**, 297 (2009).
[12] A.B. Larionov, I.A. Pshenichnov, I.N. Mishustin, and W. Greiner, *Phys. Rev.* **C80**, 021601(R) (2009).
[13] R.J. Glauber and G. Matthiae, *Nucl. Phys.* **B21**, 135 (1970).